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Final Technical Report

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"High Resolution Observations of the
Eruptive Symbiotic PU Vul"

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Scientific Report

I. Introduction

In 1979 Kuwano discovered an unusual nova in Vulpecula that has been designated PU Vul. An independent discovery by Honda as well as prediscovery observations showed that the nova slowly increased in brightess for over a year prior to Kuwano's anouncement, finally reaching a maximum visual magnitude of 8.5. The star remained near maximum for a decade, except for a peculiar dip to 14th magnitude in 1980. A detailed history of this star prior to 1987 is given by Belyakina *et al.* (1989).

At the beginning of 1988, PU Vul suddenly became a magnitude fainter (Mattei 1990, private communication) and its spectrum changed spectacularly. Prior to this event, the optical continuum was that of an A or F supergiant with weak Hα emission (Belyakina *et al.* 1989, Kenyon 1986a). By the middle of 1988 a rich emission spectrum appeared with many lines showing strong P Cygni profiles.

Infrared observations and spectra taken during minimum light reveal an M star spectrum, strongly indicating PU Vul is a symbiotic system.

The characteristics of the PU Vul outburst are strikingly similar to two slow symbiotic "novae", RR Telescopii and AG Pegasi. RR Tel brightened by seven magnitudes in 1945-46, showing an F supergiant spectrum (Thackeray 1950) until 1949. In later part of that year, emission lines of hydrogen and singly ionized iron began to dominate the spectrum. By 1952, species indicitive of high temperatures (He II, O III) had become strong (Thackeray 1953). Currently, the spectrum of RR Tel reveals a rich variety of highly ionized species including [Fe VII] and possibly [Fe XI] (Raassen 1985) although [Fe X] has not been seen.

AG Peg began its outburst in the mid-1800's, rising 3 magnitudes by 1871. In 1920, the Balmer lines displayed P Cygni profiles and He I was in emission. The ionization state of lines in the spectrum has increased, but much more slowly than in RR Tel.

We have studied the spectrum of PU Vul from 1200Å to 8200Å using IUE observations and supporting ground-based data. The number of emission lines recorded over this broad range of wavelength is impressive. Our optical spectra, obtained a year prior to and following the IUE observations, show that PU Vul is evolving relatively quickly and that the system should be regularly monitored by IUE.

II. Observations

The observations of PU Vul were carried out on a wide variety of telescopes with apertures ranging from 16 to 200 inches in diameter. The data cover three years in the development of the nova beginning in 1988. A summary of our observations is presented in Table I.

Ultraviolet spectra were obtained with the IUE satellite in September of 1989. The extreme density of emission lines required that high resolution spectra (0.6Å FWHM) be taken to separate the large number of blended lines. Low dispersion spectra were also obtained in order to characterize the underlying continuum. A log of the IUE observations is provided in Table II.

The flux calibration of the high resolution spectra was performed using the low resolution inverse sensitivity function of Bohlin and Holm (1980 IUE NASA Newsletter No.10) multiplied by a correction derived by Cassatella, Ponz and Selvelli (1981 IUE NASA Newsletter No.14). This correction for emission spectra is linear but must be extrapolated shortward of 1400Å for the SWP and 2300Å for the LWR.

PU Vul was observed during 4 runs with the 1.8m telescope at the Dominion Astrophysical Observatory. Most of the spectra were recorded with the RCA CCD at a dispersion of 30 Å/mm providing only 500Å coverage per exposure. The September 1988, July 1989 and July 1990 data covered the range of wavelengths from approximately 4000Å to 8000Å by tilting the grating at approximately 10 settings to allow plenty of overlap between consecutive spectra. The spectrophotometric standard star HD192281 was observed at the same grating tilts to determine the relative system efficiency. Poor weather in September and October 1989 prevented us from obtaining more complete wavelength coverage.

Kuwano-Honda's nova was also observed at Palomar with the 5m telescope and the double spectrograph in the summer of 1988. This instrument divides the incoming light with a dichroic beamsplitter and records a red and a blue spectrum simultaneously on two CCD detectors. The blue channel was set to record wavelengths from 3200Å to 3600Å while the red channel covered 600Å centered at 7000Å . The Palomar standard stars BD $+26^{\circ}2606$ and BD $+17^{\circ}4708$ (Oke and Gunn 1983) were observed in order to flux calibrate the data.

III. Results

The spectra of PU Vul in the UV and optical are remarkable for the number of lines recorded and for the variety of their profiles. Table III lists some of the important lines we identified from the IUE spectra obtained in September 1989. In addition, nearly 300 lines of Fe II, Ni II and Ti II are also present. A similar number of lines have been identified at optical wavelengths. Lines of Si IV $\lambda1394$, $\lambda1403$ show broad P Cygni profiles. Narrow P Cygni profiles are seen in H I, He I and, a number of interstellar absorption lines are present.

The low excitation of the observed species in both the UV and optical spectra indicate PU Vul is approximately at the stage of development that RR Tel reached in 1951. This is demonstrated by the weakness of the He II λ1640 in the IUE spectra and the rapid increase in strength of the He II λ4686 between 1989 and 1990. Thus, PU Vul is evolving twice as slowly as RR Tel, and five times faster than AG Peg (although the limited data on AG Peg at this stage of development makes a rate estimate uncertain). We suggest that the spectral evolution rate is related to the outburst amplitude. The outburst amplitudes in the visual are 3, 5-6, and 7 (Kenyon 1986b) for AG Peg, PU Vul and RR Tel respectively. This relationship is analogous to the well known amplitude, decline rate correlation for classical novae.

The most striking feature seen in the long wavelength (LWP) IUE spectrum of PU Vul is the strong pair of lines at λ2506 and λ2508. These lines are present in RR Tel and AG Peg although much less intense. They remained unidentified until Johansson and Jordan (1984) showed that many lines in the UV spectra of cool giants result from fluorescence of Fe II by Lyα photons. The strength of the λ2506 and λ2508 lines in PU Vul and the lack of any Lyα emission (excluding geocoronal) suggests a large volume around PU Vul remains optically thick to Lyα but thin to the Fe II lines at 2500Å. The trapped Lyα photons scatter in this volume until they excite Fe II transitions near 1218Å, which cascade through λ2506 and λ2508 and escape.

One of the most intriguing aspects of our spectra of PU Vul during 1988 and early 1989 is the detection of the famous unidentified line at 6830Å. This line has only been seen in symbiotic stars and is often one of the brightest emission lines at visible wavelengths. It is associated with high excitation symbiotics since it is seen along with [Fe VII] and [Ne V] (Allen 1980). Because it is readily visible on low dispersion spectra, 6830Å is often used as a measure of excitation for faint symbiotics.

Recently, Schmid (1989) has proposed that the line is the result of Raman scattering of O VI photons by neutral hydrogen near the cool giant star. The theory is attractive for a number of reasons.

1) Explains the high excitation associated with the line.

2) Explains the observed width (typically 20Å) of the line.

3) Explains the appearence of the associated unidentified line at 7090Å (Allen 1978).

The O VI lines responsible for the Raman scattering are at 1032Å and 1038Å and not directly observable even by IUE. Johansson (1988), however, has indirectly observed these lines by identifying Fe II emission in the IUE spectrum of RR Tel that are fluoresced by O VI photons. The strong O V recombination line in RR Tel and other high excitation symbiotics also implies that the O VI lines at 1032Å and 1038Å are present (Hayes and Nussbaumer 1986).

A simple application of the Raman scattering hypothesis for the origin of the 6830Å band can not explain its presence in the spectrum of PU Vul in 1988 and early 1989. The following problems arise:

1) No evidence suggests that O VI exists in the PU Vul system.

   a) The He II lines at $\lambda1640$ and $\lambda4686$ are weak, indicating a temperature far too low for O VI to be abundant.

   b) The Fe II line at 1776Å, which is fluoresced by O VI, is not present in PU Vul.

   c) The recombination line of O V at 1371Å is not present.

2) The unidentified line at 7090Å is not seen in PU Vul but is also expected to be produced by the Raman scattering.

The Raman scattering theory is still viable if we assume the very hot region containing O VI is obscured from our view, but visible to the cool giant star which provides the neutral hydrogen needed for the scattering. Such a geometry will have other observational consequences which should be testable in the future.

References

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TABLE I

Log of Observations

Date	Observatory/ Telescope	Wavelength coverage	Resolution	Comments
July 01–02, 1988	Palomar 5m	3200–3600Å	1.3Å	
July 01–02, 1988	Palomar 5m	6700–7300Å	2.0Å	
Sept 01–05, 1988	DAO 1.8m	3750–8200Å	2.7Å	
July 21–23, 1989	DAO 1.8m	3800–7600Å	2.7Å	
Sept 16–17, 1989	DAO 1.8m	6400–6900Å	2.7Å	1
Sept 25–26, 1989	IUE	1200–3300Å	6 Å	2
Sept 25–26, 1989	IUE	1200–3200Å	0.2Å	2
Oct 10–11, 1989	DAO 1.8m	3600–6000Å	5.4Å	1
July 21–22, 1990	DAO 1.8m	4000–7100Å	2.7Å	

1) No sensitivity calibration

2) Absolute flux calibration

TABLE II

Log of IUE Observations

Camera Sequence	Date (UT 1989)	Disp.	Exposure Time (s)	Comments
SWP 37184	Sept 25	LO	1000	
LWP 16416	Sept 25	LO	320	pseudotrailed
SWP 37185	Sept 25	LO	1800	>1750Å saturated
LWP 16417	Sept 25	HI	2100	
LWP 16418	Sept 25	HI	4200	
SWP 37190	Sept 26	HI	24960	

TABLE III

Lines in the UV Spectrum of PU Vul

λ_{ID} Vac	Ident. (mult.)	λ_{obs}	Flux 10^{-13} ergs s^{-1}	Comments
1215.67	H I	1215.63	38.4	Lα Geocoronal
1302.17	O I (2)	1302.57	14.3	
1304.86	O I (2)	1305.12	24.8	
1306.03	O I (2)	1306.31	32.5	
1335.66	C II (1)	1335.90	20.4	P Cygni, broad
1393.76	Si IV (1)	1394.66	27.4	P Cygni, broad
1402.77	Si IV (1)	1403.37	32.1	P Cygni, broad
1411.94	N I (10)	1412.18	11.0	
1483.27	N IV]	1484.00	3.6	broad
1486.48	N IV]	1486.96	13.4	broad
1533.44	Si II (2)	1533.23 1533.81	−2.0 3.5	absorption
1546.92	Fe III	1547.70	14.8	
1606.01	Fe III (119)	1606.43	20.7	broad
1640.49	He II	1641.01	9.1	
1664.51	Si I (24)	1664.85	19.7	broad
1671.12	Si I (23)	1671.73	7.5	broad
1700.42	Si I (18)	1700.80	20.2	
1740.30	Si I (80)	1740.86	7.4	
1742.73	N I (9)	1743.10	11.9	
1743.88	Si I (79)	1744.55	3.1	
1745.25	N I (9)	1745.55	11.3	
1746.82	N III (0)	1747.40	7.1	
1748.70	N III (0)	1749.36	4.8	
1749.70	N III (0)	1750.39	2.9	
		1750.99	3.2	
1752.20	N III (0)	1752.75	8.1	
		1753.60	11.6	
1760.10	Al II (5)	1760.49	10.7	
1808.01	Si II (1)	1807.93 1808.36	−2.1 3.8	P Cygni
1817.42	Si II (1)	1817.79		+ Si II (1) 1816.94
1829.90	Si I (12)	1830.23	12.9	
1854.72	Al III (1)	1854.72 1855.25	−2.6 29.1	absorption
1862.78	Al III (1)	1860.74 1863.27	−2.0 14.7	
1869.53	Fe II	1869.76	10.8	Fluoresced by Lyα
1871.01	Fe II	1871.30	6.3	Fluoresced by Lyα
1872.64	Fe II	1872.87	7.8	Fluoresced by Lyα

TABLE III con't.

λ_{ID} Vac	Ident. (mult.)	λ_{obs}	Flux 10^{-13} ergs s^{-1}	Comments
1884.19	Si III]	1884.31	3.2	
1892.03	Si III] (1)	1892.20	64.0	double peaked, saturated
1895.46	Fe III (34)	1896.52	10.0	
1914.06	Fe III (34)	1914.31	55.2	
Air				
2139.01	N II (0)	2139.10	22.3	
2142.78	N II (0)	2143.05	23.9	
2418.57	Fe III (47)	2418.89	20.5	
2430.43	Fe I	2430.81	14.1	
2438.17	Fe III (47)	2438.51	14.5	
2504.89	Fe II	2505.12	7.5	Fluoresced by Lyα, weak
2506.43	Fe II	2506.87	>41.3	Fluoresced by Lyα, saturated
2506.80	Fe II	2507.44	23.4	Fluoresced by Lyα, blend
2508.34	Fe II	2508.56	>51.4	Fluoresced by Lyα, saturated
2669.17	[Al II]	2669.52	53.5	
2790.77	Mg II (3)	2791.35	6.0	+ Fe II 2790.75
2797.99	Mg II (3)	2798.49	12.8	
2795.52	Mg II (1)	2794.62 2795.67 2796.65	16.5 −1.7 81.1	absorption
2802.71	Mg II (1)	2801.88 2802.53 2803.68	11.0 −1.4 72.1	absorption
2852.13	Mg I (1)	2851.72 2852.24 2852.59	2.8 −3.6 9.5	absorption
2936.50	Mg II (2)	2936.91	5.1	

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QUALITY CONTROL

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RPA: Y	FST: GDR	ACR:	FOI: HC	LNG: EN	CIN: KMA
MUR: OK	POT: 19900831	LCA:	DCL: TRP	CAT: 89	DIN:
MCP: Z	PAG: 9	FRR:	DSC: NC	CSC:	KIN:
MCS: 9	OCF:	RVD: 0	TSC: NC	ALI: N	AIN:
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COR: US UNITED STATES
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1) SRC: wf835159 - Washington Univ., Seattle.
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UTL: High resolution observations of the eruptive symbi
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